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Spatio-temporal impact of climate change on the groundwater system

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Abstract

Given the importance of groundwater for food production and drinking water supply, but also for the survival of groundwater dependent terrestrial ecosystems (GWDTEs) it is essential to assess the impact of climate change on this freshwater resource. In this paper we study with high temporal and spatial resolution the impact of 28 climate change scenarios on the groundwater system of a lowland catchment in Belgium. Our results show for the scenario period 2070–2101 compared with the reference period 1960–1991, a change in annual groundwater recharge between −20 % and +7 %. On average annual groundwater recharge decreases 7 %. Seasonally, in most scenarios the recharge increases during winter but decreases during summer. The altered recharge patterns cause the groundwater level to decrease significantly from September to January. On average the groundwater level decreases about 7 cm with a standard deviation between the scenarios of 5 cm. Groundwater levels in interfluves and upstream areas are more sensitive to climate change than groundwater levels in the river valley. Groundwater discharge to GWDTEs is expected to decrease during late summer and autumn as much as 10 %, though the discharge remains at reference-period level during winter and early spring. As GWDTEs are strongly influenced by temporal dynamics of the groundwater system, close monitoring of groundwater and implementation of adaptive management measures are required to prevent ecological loss.

1 Introduction

There is little doubt that the ongoing climate change will significantly influence the hydrological cycle worldwide (Kundzewicz et al., 2008; Maxwell and Kollet, 2008). Current observations show that already at this moment climate changes are influencing hydrological processes in certain areas (Rosenzweig et al., 2007; Kundzewicz and Döll, 2009). As the IPCC predicts that global atmospheric concentrations of greenhouse gases will continue to rise, it is expected that climate change will continue in the future (Solomon et al., 2007). Freshwater resources are among those systems that are particularly vulnerable to changes in climate (Solomon et al., 2007).

Recent research (Feyen and Dankers, 2009) showed that global warming is likely to amplify drought events over Europe. Especially during drought events groundwater is of vital importance for availability of water for food production and drinking water. Groundwater plays a vital role in maintaining the ecological value of many areas (Solomon et al., 2007; UN WWAP, 2009). Because groundwater is less visible and has a more complex relationship with the climate than surface water bodies it has been studied less than surface water bodies up till now (Kundzewicz and Döll, 2009; Scibek et al., 2007). However, there is an increasing awareness to protect the groundwater resources and to assess the impact of future land-use and climate changes (Solomon et al., 2007; Green et al., 2011).

In order to assess the impact of climate change on the groundwater system there is a need for reliable climate change scenarios and consistent methods to simulate water fluxes recharging and discharging the groundwater system. The uncertainty on climate change forecasts is still very high due to uncertainties in the future world visions, influencing for example the emissions of greenhouse gas, land use changes, etc. and uncertainties caused by the General and Regional Circulation Models (GCMs and RCMs) (Murphy et al., 2004). In order to optimally incorporate the current knowledge on climate change, Kundzewicz et al. (2008) and Allen et al. (2010) suggest a joint analysis of ensembles of climate models driven by multiple emission scenarios. Hendricks Franssen (2009) emphasizes the importance of downscaling of future precipitation from GCMs for impact assessments on hydrology.

Previous studies show a large variety in complexity of approaches to simulate groundwater recharge. For example Chen et al. (2002), Hsu et al. (2006) and Serrat-Capdevila et al. (2007) apply a simple linear function including precipitation and temperature to simulate groundwater recharge, while Woldeamlak et al. (2007), Jyrkama and Sykes (2007), van Roosmalen et al. (2009), McCallum et al. (2010) amongst others apply a more complex approach. Jyrkama and Sykes (2007), Hendricks Franssen (2009), Ferguson and Maxwell (2010) and Holman (2006) advise a physically based approach that accounts for spatial and temporal variation of surface and subsurface properties of the study basin when simulating the impact of climate change on groundwater recharge. A majority of the current studies assessing the impact of climate change on the groundwater system estimate the impact on the annual or seasonal average spatially distributed recharge, e.g., Dickinson et al. (2004), Scibek and Allen (2006), Scibek et al. (2007), Serrat-Capdevila et al. (2007) and Woldeamlak et al. (2007). Woldeamlak et al. (2007) stated that climate change impact studies based on steady-state groundwater simulation have limitations in representing boundary conditions and can only be used for assessing sensitivities. A few recent studies have applied transient methods to estimate the impact of climate changes on the groundwater system (van Roosmalen et al., 2009; Goderniaux et al., 2009; Jackson et al., 2011). However, both van Roosmalen et al. (2009) and Goderniaux et al. (2009) limit the analysis of the transient results to the predicted change in some observation wells. Nevertheless, the groundwater dynamics within a year is of major importance for groundwater dependent terrestrial ecosystems (GWDTEs) (Naumburg et al., 2005). Groundwater dependent vegetations along with riverine landscapes have an important ecological function (Naumburg et al., 2005) and should therefore be protected. Applying highly dynamic models also allows including more accurately changes in precipitation intensity and number of dry and wet days projections due to climate change. Precipitation intensity and number of wet and dry days have an important impact on the soil moisture content and consequently influence strongly the groundwater recharge.

This is one of the first studies analyzing the intra-annual response of a groundwater system to climate changes. These intra-annual changes determine the status of the groundwater resources as well as site conditions of GWDTEs (Naumburg et al., 2005). The climate for the reference period, 1960–1991, is compared with climate scenarios, predicted for 2070–2101. Due to the high variability of climate change predictions between different climate change models, an ensemble of 28 climate change scenarios is chosen from the European project PRUDENCE (Christensen and Christensen, 2007). By applying this ensemble of climate change models we obtain uncertainty bounds on the impacts of the climate change on the groundwater system. We limit the study to climate change impacts, disregarding other expected changes such as land-use change (Dams et al., 2008).

The Kleine Nete basin, situated in Belgium, was chosen as a study area. Due to the sandy soils and low slopes a large fraction of the effective rainfall in the basin percolates to the groundwater. The groundwater in the basin is extensively used for drinking water supply, and hosts important groundwater dependent wetlands. An impact assessment is therefore required to assess whether adaptive measures are essential to protect the groundwater system and related groundwater dependent natural vegetations from expected climate changes.

2 Study area

The study area is the Kleine Nete basin, which is a sub-basin of the Scheldt basin (Fig. 1). The Kleine Nete basin has an area of 581 km^2.The elevation ranges from 3 to 48 m TAW, the average slope is about 0.4 %. Interfluves are slightly elevated, the valleys broad and swampy. The dominant soil texture in the basin is sand, though in the valleys some loamy sand, sandy loam and sandy clay is present. The region has a temperate climate characterized by a warm summer and a cool winter with little snowfall. The average annual precipitation during the period 1960–1991 was 828 mm with a standard deviation of 136 mm. Precipitation is nearly equally distributed throughout the year and the different raingauges, indicated in Fig. 1, show similar annual precipitation amounts. Over the same period 1960–1991 the estimated average annual potential evapotranspiration (PET) is 664 mm with a standard deviation of 47 mm. The subsurface of the model area is limited to the Quaternary and Tertiary sediments which are confined at the bottom by the Boom clay aquitard deposited during the Oligocene epoch. From depositionally oldest to youngest the hydrostratigraphy of the study area comprises the Miocene aquifer, the Pliocene clay layer, the Pleistocene and Pliocene aquifer, the Campine clay-sand-complex and the Quaternary aquifer. An overview of the formations is given in Table 1. Only the Miocene aquifer and the Quaternary aquifer are found throughout the basin, other hydrostratigraphic units are discontinuous as shown in Fig. 2. Figure 3 shows a 3-D view of the geological layers along a cross-section over the area. The Miocene aquifer has an average thickness of about 187 m and in the eastern part of the basin this aquifer reaches a maximum thickness of 410 m (Wouters and Vandenberghe, 1994).

The land cover in the study area consists mainly of agricultural fields including meadows (60 %), coniferous and mixed forest (20 %) and urban areas (10 %). Groundwater is extensively used in the basin, in total there are 565 wells which extract a total of 54 291 m^3 day^{-1} of which about 30 200 m^3 day^{-1} is extracted by a single water production company for drinking water supply. Most important pumping wells are indicated in Fig. 1.

Within the Kleine Nete catchment several ecologically important areas are protected by the European Natura2000 network, set up for the protection of Europe's most vulnerable habitats. Several of these habitats depend largely on oligotrophic and mesotrophic site conditions, influenced by groundwater flow conditions. Typical habitats are Northern wet heaths, Shady woodland fringes, Atlantic Quercus robur – Betula woods, Alnus–Fraxinus woods, etc.

3 Data and method of analysis

This study compares the groundwater characteristics of a lowland watershed in Belgium for the reference period 1960–1991 with those subject and under climate change conditions for the period 2070–2101. Figure 4 shows a conceptual overview of the applied spatial-temporal methodology. An ensemble of 28 climate change scenarios derived from multiple GCMs and RCMs and driven by multiple greenhouse emission scenarios is applied.

3.1 Climate change

Climate change scenarios are obtained from the PRUDENCE database and combine several GCMs: ECHAM4/OPYC, HadAM3H, HadAM3P, ARPEGE and HadCM3 and RCMs: RCAO, RACMO, HIRAM, CHRM, HadRM3P, REMO, ARPEGE, CLM and PROMES (Christensen and Christensen, 2007). All scenarios applied in this research are based on the A2 and B2 SRES greenhouse gas emission scenarios of the Intergovernmental Panel for Climate Change (IPCC) (Nakicenovic and Swart, 2000). In total, projections from 28 climate models runs were statistically analyzed, comparing the daily simulation results for precipitation and PET between the control period 1960–1991 and the scenario period 2070–2101. The precipitation results were obtained directly from the RCM outputs, and PET was calculated by Baguis et al. (2009) using the Penman equation based on the RCM outputs of mean sea level pressure, net terrestrial radiation, total solar radiation, cloud cover, temperature at 2 m, wind at 10 m and humidity. For each RCM simulation, the monthly changes from the control period to the scenario period were statistically analyzed in terms of changes in wet day frequencies (for precipitation) and wet day relative intensity changes (for precipitation and PET). The combination of frequency- and quantile-pertubation techniques allow to determine both the relative magnitude of the changes and the changes in extreme events. The intensity changes for precipitation were analyzed in relation to the exceedance probability of each intensity (Ntegeka et al., 2008). The changes in wet day frequencies and intensities were applied as changes to the historical time series (control period) with a daily time step using a statistical perturbation procedure (Ntegeka et al., 2008). More details on the frequency- and quantile-perturbation procedure can be found in Ntegeka and Willems (2008) and Willems and Vrac (2011).

3.2 Groundwater system modeling

The impact of climate change on the groundwater system is simulated by applying a coupled WetSpa – MODFLOW approach. WetSpa (Liu et al., 2003), a physically based distributed hydrological model, simulates with a daily time step the river discharge at the outlet of the basin and the groundwater recharge for each 50 by 50 m model cell in the watershed. WetSpa updates the root zone water balance for all model cells during each timestep (Safari et al., 2011):

$$D\frac{\partial\theta}{\partial t} = P - I - S - \mathrm{ET} - R - F \tag{1}$$

where D [L] is root depth, θ [$\mathrm{L^3\,L^{-3}}$] soil moisture, P [$\mathrm{L\,T^{-1}}$] precipitation, I [$\mathrm{L\,T^{-1}}$] initial loss including interception and depression storage, S [$\mathrm{L\,T^{-1}}$] surface runoff, ET [$\mathrm{L\,T^{-1}}$] evapotranspiration, R [$\mathrm{L\,T^{-1}}$] percolation out of the root zone, F [$\mathrm{L\,T^{-1}}$] interflow, t [T] is time. The evapotranspiration flux includes, evaporation, transpiration from the root zone and direct uptake of groundwater by plants.

The rate of percolation (R_{rate}) or groundwater recharge in the WetSpa model is derived through the Brooks and Corey relationship (Brooks and Corey, 1964):

$$R_{\mathrm{rate}} = K(\theta) = K_{\mathrm{s}}\left(\frac{\theta-\theta_{\mathrm{r}}}{\theta_{\mathrm{s}}-\theta_{\mathrm{r}}}\right)^{3+\left(\frac{2}{B}\right)} \tag{2}$$

where $K(\theta)$ [$\mathrm{L\,T^{-1}}$] is the unsaturated hydraulic conductivity, K_{s} [$\mathrm{L\,T^{-1}}$] saturated hydraulic conductivity, θ_{s} [$\mathrm{L^3\,L^{-3}}$] water content at saturation, θ_{r} [$\mathrm{L^3\,L^{-3}}$] residual soil moisture content, and B [–] is the soil pore size distribution index. The soil pore size distribution index B is obtained from an empirically derived univariate regression, based on the percentage of clay content (Cosby et al., 1984).

Daily spatially distributed recharge results are aggregated over half monthly periods to be compatible with the MODFLOW time step. Additionally, the results of a hydraulic model for the main rivers in the basin are used to obtain half monthly average river heads for every 50 m transect of those rivers, based on WetSpa simulated river discharge at the basin outlet.

The groundwater flow model MODFLOW (Harbaugh et al., 2000) simulates the effect of the climate induced changes in river head and groundwater recharge on the groundwater level and flux. The watershed boundaries of the model are set to no-flow boundaries. A conceptual hydrogeologic model is simulated using two model layers. The top layer of the model combines all hydrogeologic units except the Miocene aquifer, which is solely represented by the bottom model layer. The initial horizontal and vertical hydraulic conductivity are calculated using respectively the weighted arithmetic and harmonic mean of the hydraulic conductivities of the individual layers. To incorporate the inter-layer variability of hydraulic conductivity and specific yield within the upper MODFLOW layer, this layer is sub-divided into seven zones with different calibration multipliers. All major rivers, canals and lakes are simulated as internal boundaries and parameterized with the RIVER package. The RIVER package controls the flux exchanged between the groundwater system and the river, based on the river stage, the elevation of the bottom of the riverbed, the riverbed hydraulic conductance and the hydraulic head calculated for the particular model cell containing the surface-water feature. The river stage for the main rivers is adapted based on the WetSpa simulated river discharge at the outlet. The groundwater drainage from ditches, small streams and wetlands is simulated using the DRAIN/SEEPAGE package (Batelaan and De Smedt, 2004). In this module the flow to a drain is calculated depending on the drainage level and conductance. The drainage level is set to the highest location in the soil profiles where oxidation appears.

Because the ability of the models to simulate groundwater recharge and discharge is important in this paper, the baseflow is integrated in the calibration procedure. A measured baseflow timeseries is extracted using the baseflow filter developed by Arnold and Allen (1999). Figure 5 compares for the calibration period the baseflow extracted by the baseflow filter with the simulated baseflow of WetSpa and MODFLOW. It is shown that the baseflow simulated with the WetSpa model is very simular to the baseflow derived from the baseflow filter. The MODFLOW model, while using the WetSpa simulated recharge, tends to underestimate high baseflows. The WetSpa model was calibrated using measured river discharges and estimated baseflow at the catchment outlet. A Nash-Sutcliff efficiency of 73 % was obtained for the river discharge and 87 %

for the baseflow. The MODFLOW model is calibrated using 10 226 head observations measured between 1991 and 2001 from 113 observation wells (Fig. 1) more or less equally distributed over the basin. After calibration the MODFLOW model has an average bias between observed and simulated hydraulic head of −0.03 m, a mean average error of 0.59 m and a root mean square error of 0.81 m.

3.3 Groundwater level and flux analyses

In order to reduce the effect of the initial conditions, results of initial time steps are not used. The mean highest groundwater level (MHGL), mean lowest groundwater level (MLGL) and mean spring groundwater level (MSGL) are calculated respectively as the three highest, the three lowest and the three groundwater level measurements around the 1st of April per year, based on two weekly measurements, and averaging these values over at least eight years (Van der Sluijs and De Gruijter, 1985). In this study the MHGL, MLGL and MSGL for each model cell are estimated based on the half monthly groundwater level simulated by MODFLOW. The groundwater discharge frequency is calculated as the percentage of time steps in which a groundwater discharge to SEEPAGE and RIVER cells is simulated for every 50 by 50 m cell of the MODFLOW model.

4 Results and discussion

4.1 Intra-annual impact of climate change on groundwater characteristics

Figure 6a illustrates the projected intra-annual change in PET, obtained from averaging the 32 yr simulation period. The average yearly PET of 664 mm yr^{-1} measured during 1960–1991 is predicted to increase almost 30 % with a standard deviation between the scenarios of 91 mm yr^{-1}. The increase in PET occurs almost completely between April and October. Figure 6b shows the reference and forecasted average precipitation within the basin for each time step. The total annual precipitation decreases on average by 50 mm, from 821 to 771 mm yr^{-1} with a standard deviation of 35 mm between the scenarios. As observed from Fig. 6b the change in precipitation varies in time: from October to April the precipitation increases on average 50 mm but from May to September the precipitation decreases about 100 mm. Figure 6c illustrates the average annual groundwater recharge pattern, which follows roughly the combined effect of precipitation minus PET. The already low groundwater recharge during summer decreases due to higher evapotranspiration and lower precipitation, on the other hand additional precipitation during winter causes the groundwater recharge to increase. On average the groundwater recharge is predicted to decrease about 40 mm during summer and increase about 20 mm during winter, resulting in an annual decrease from 278 to 258 mm yr^{-1} or 7.2 %. The standard deviation of the change in yearly groundwater recharge calculated from the different climate scenarios is 20 mm. Figure 6d shows that the simulated groundwater head is less variable than the highly dynamic precipitation and groundwater recharge, due to the moderating effect of the flow system. In April the average simulated future groundwater head is close to the average reference head. During summer however, the climate scenarios predict a larger seasonal groundwater storage depletion. The maximum average groundwater depth simulated for the reference period is 2.2 m below the topography and is reached during the first half of September, while the maximum average future groundwater depth predicted by the climate scenarios is 2.3 m and occurs later at the end of September. The timing of the minimum average groundwater depth also shifts, from late December–January to early February–late March. The maximum average difference in simulated groundwater depth between the reference period and the future scenarios occurs in November, when the average simulated future groundwater depth is about 15 cm greater. Over the entire year the average reference simulated groundwater head declines about 7 cm. Figure 6e displays the average intra-annual groundwater discharge simulated for the reference period and future scenarios. Similar to the groundwater head we observe that the average future groundwater discharge decreases at a greater rate during summer compared to the reference scenario, however, also the increase of the average groundwater discharge during autumn is more profound for the future scenarios. The average future groundwater discharge from February until May fluctuates around the groundwater discharge simulated for the reference climate. On the other hand, from August until December the groundwater discharge is predicted to decrease by more than 10 %.

4.2 Impact of climate change on average and extreme groundwater heads

Figure 7 illustrates the spatial impact of the climate change scenarios on the groundwater head. Compared with the reference scenario the groundwater head decreases most on the interfluves and near the fringes of the watershed where the average groundwater level can be as much as 30 cm lower. In the valleys the average groundwater level decrease is generally less than 5 cm (Fig. 7a). For GWDTEs, especially the yearly extreme groundwater depths (MHGL, Fig. 7b and MLGL, Fig. 7c), and the MSGL (Fig. 7d) influence the plant species distribution. Both the MLGL and the MHGL show a generally decreasing trend. Similar to the average groundwater levels, the interfluves are more sensitive and show the greatest decrease in yearly extreme groundwater levels. From Fig. 7b–d we notice that the largest decrease is obtained for the MLGL, for which an average decrease of 6 cm is simulated, with a standard deviation of 3 cm between the scenarios. The MHGL and MSGL decrease on average 3 and 1 cm, respectively. The standard deviation between the different scenarios is 5 cm for both MHGL and MSGL.

4.3 Impact of climate change on groundwater discharge

The climate also influences the groundwater interaction with surface water and groundwater discharge towards the land surface. Sufficient groundwater exfiltration is crucial for the presence of GWDTEs. Figure 8 presents for all model cells of the catchment the change in groundwater discharge flux, averaged over time, between the reference condition and the average of all future scenarios. The scenarios predict for most cells a decrease in average groundwater discharge. Figure 8 also shows that the maximum decrease is about 50 %. The highest decrease in groundwater discharge occurs in cells with a reference groundwater discharge flux of less than 1 mm d^{-1} where the average decrease is about 15 %. Groundwater discharge cells with a reference flux between 1 and 10 mm d^{-1} seem to be buffered quite well to the predicted climate changes. The average total groundwater discharge from the basin decreases from 5.0 to 4.8 $m^3 s^{-1}$ for the reference scenario and the average of the future scenarios, respectively.

In addition to the magnitude of groundwater discharge, the temporal availability of groundwater is important for GWDTEs. Figure 9 plots the change in groundwater discharge frequency versus the reference groundwater discharge frequency. The groundwater discharge frequency of a cell is the temporal frequency that groundwater discharge occurs from this cell. Figure 9 shows that there is an average decrease in the frequency of groundwater discharge. The magnitude of groundwater discharge frequency will especially decrease for zones which originally had a groundwater discharge frequency between 40 and 90 %.

5 Conclusions

This paper discusses how climate changes alter the spatio-temporal dynamics of the groundwater system. Until now hydrological impact assessment of climate change has been focused primarily on peak flows and flood events. However, most GCMs predict that global warming is likely to amplify drought events over Europe. Consequently, there is a growing concern on the future availability of water for drinking water supply, crop growth and natural vegetations throughout the year. Hence, there is an urgent need for more research on the impact of those drought events on low flows and on the groundwater system.

Our paper is one the first that analyzes the impact of climate change on the groundwater system with a high spatio-temporal resolution at the watershed scale. Applying this high spatial and temporal resolution showed that the impact is highly variable both in space and time. We found that for our study area, situated in Western Europe, the ensemble average of 28 climate change scenarios predict a decrease in summer groundwater recharge causing reduced groundwater heads and lower groundwater discharge fluxes especially in late summer-early autumn. Because of the increasing precipitation during winter the groundwater head and flux during spring are expected to decrease only slightly. Groundwater level changes are shown to be more pronounced on the interfluves and upstream in the catchment. The MHGL, MLGL and groundwater discharge frequency are likely to decrease at most places. The results also indicate the importance of applying transient climate change impact assessments due to the seasonal variations of the changes.

Additionally, our research shows the importance of applying an ensemble of climate change predictions. By applying 28 different climate scenarios obtained from different GCMs and RCMs we indicate the uncertainties associated with the results. As the uncertainties of the climate scenarios are large the additional uncertainties from the hydrological and groundwater flow models are not additionally taken into account. Due to the large uncertainties in the predictions of climate variables, especially precipitation, the predicted impact on the groundwater system obtained in this research should be considered as trends and order of magnitudes rather than exact predictions.

To reduce model calculation time and increase the model stability a loose coupling is applied between the surface water model Wetspa and the groundwater flow model MODFLOW. Further research should examine how models could be improved for assessing the impact of climate changes on the groundwater system, for example by including vegetation growth, physically based ET calculation, hourly time discretization, further coupling of surface-subsurface processes without increasing the data requirements and computation time too excessively.

Although it is advisable to mitigate climate change as much as possible it has become clear over the past decade that we will also have to adapt to climate change. To prevent the loss of groundwater dependent vegetation and reduced crop growth due to drought problems, resource managers should consider adaptive measures as soon as possible. An important message from the results is that GWDTEs are especially

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vulnerable due to too low summer groundwater levels and reductions in the magnitude and frequency of groundwater discharge to the landscape.

Because climate models predictions are highly variable spatially (Solomon et al., 2007; Hendricks Franssen, 2009) similar research should be done for different hydroclimatologically and hydrogeological type locations to gain insight into the meteorological and basin characteristics controlling the impacts of climate change on groundwater systems.

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Table 1. Overview of the hydrostratigraphy of the study area.

Aquifer code (HCOV)	Aquifer name	Hydraulic conductivity [$\mathrm{m\,d^{-1}}$]	
		Mean	Range
0100	Quaternary aquifer	4.8	1–20
0220	Campine Clay-sand complex	9.4	5–15
0230	Pleistocene and Pliocene aquifer	20.5	4–40
0240	Pliocene clay layer	0.1	0.04–0.2
0250	Miocene aquifer	14.1	3–30

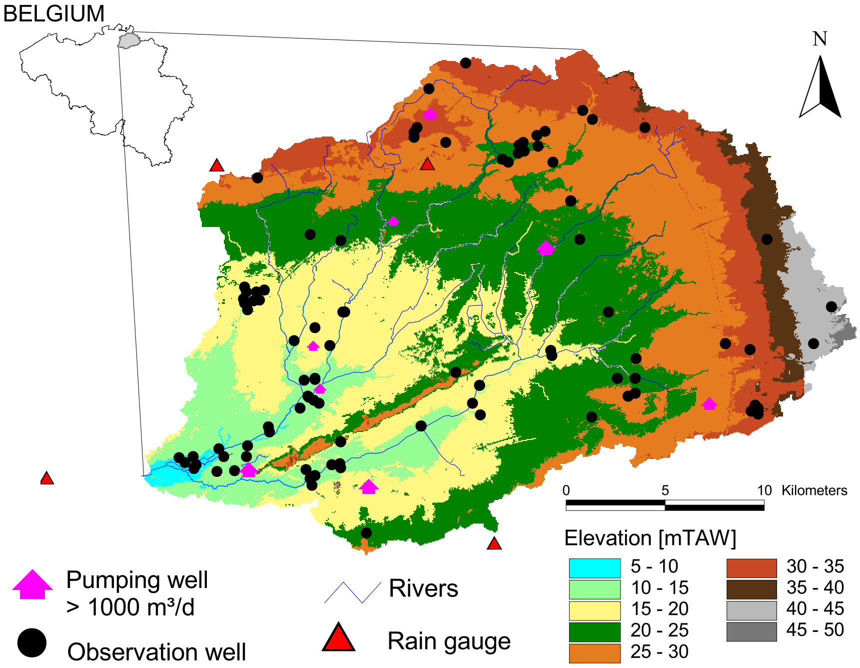

Fig. 1. Location and topography of the study area including the geographical position of the observation and most important pumping wells and rain gauges.

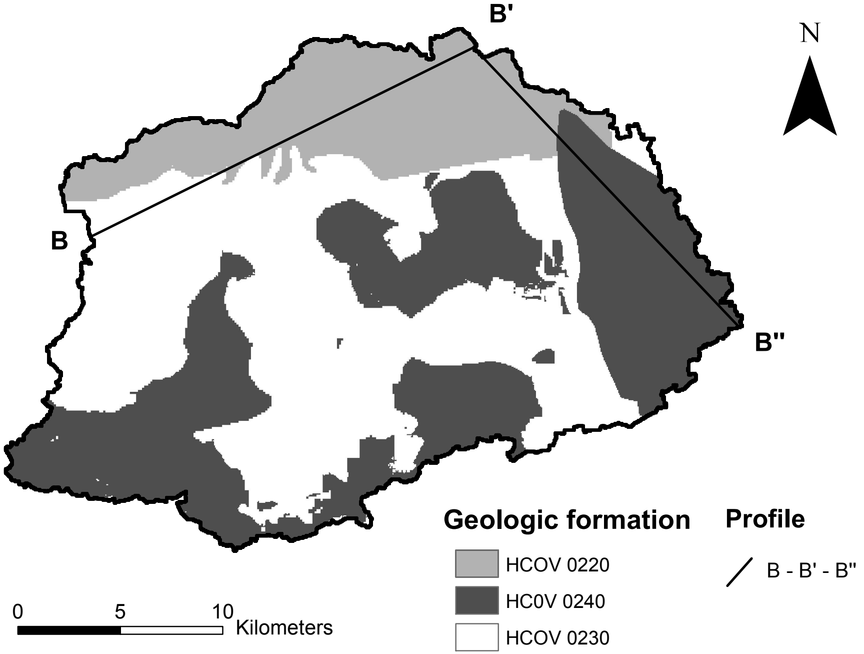

Fig. 2. Occurrence of Tertiary formations, the formations are described in Table 1. The profile B-B′-B″ is presented in Fig. 3.

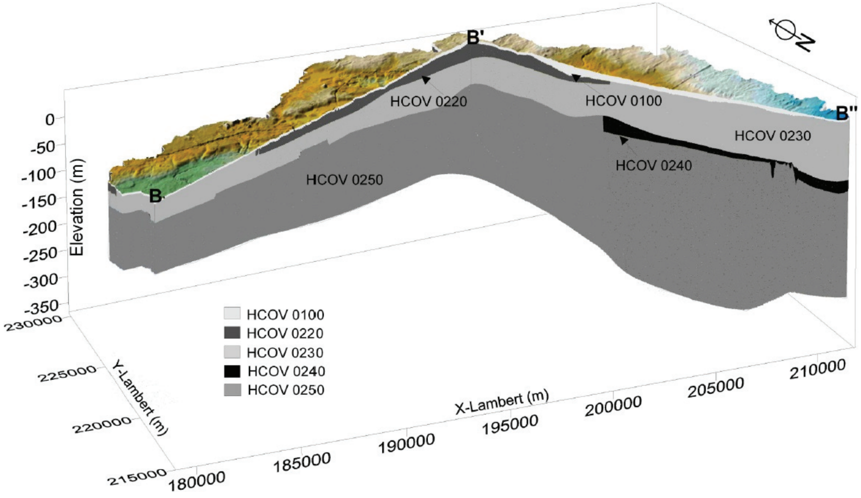

Fig. 3. Cross-section along profile B-B′-B″ presented in Fig. 2 showing the different Tertiary formations. The HCOV aquifer codes are given in Table 1.

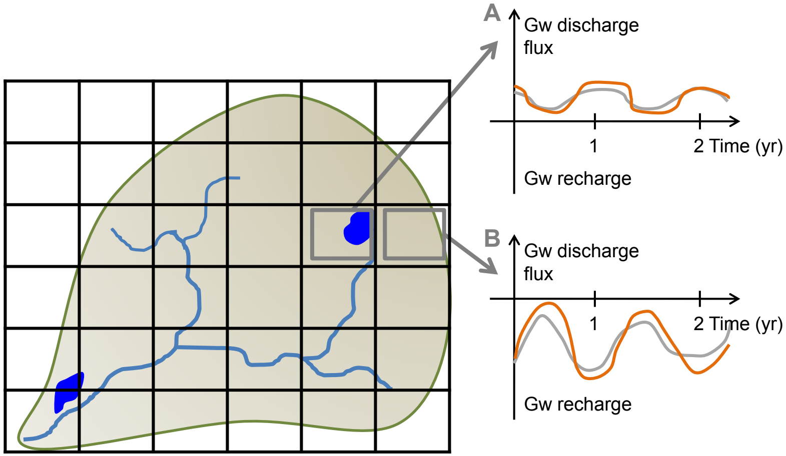

Fig. 4. Conceptual overview of the applied spatial-temporal methodology. The figure shows a watershed discretized using a rectilinear grid, surface water bodies are represented in blue. For every cell all waterbalance components are simulated daily and the runoff, interflow and groundwater flow are routed to the outlet of the catchment. Recharge and discharge are aggregated to halfmontly time steps. Two cells in this figure are highlighted. Cell A represents a typical groundwater discharge area: during most time steps the groundwater in this cell flows from the groundwater system towards the land surface where the groundwater can discharge to the surface water bodies or be used for evapotranspiration. Cell B represents a typical recharge area where the water table is recharged by water infiltrating from the land surface. The graphs on the right show how the groundwater discharge or recharge flux typically evolve over time. In this study the groundwater system is simulated for the reference condition (grey line) and several climate change scenarios (e.g. orange line).

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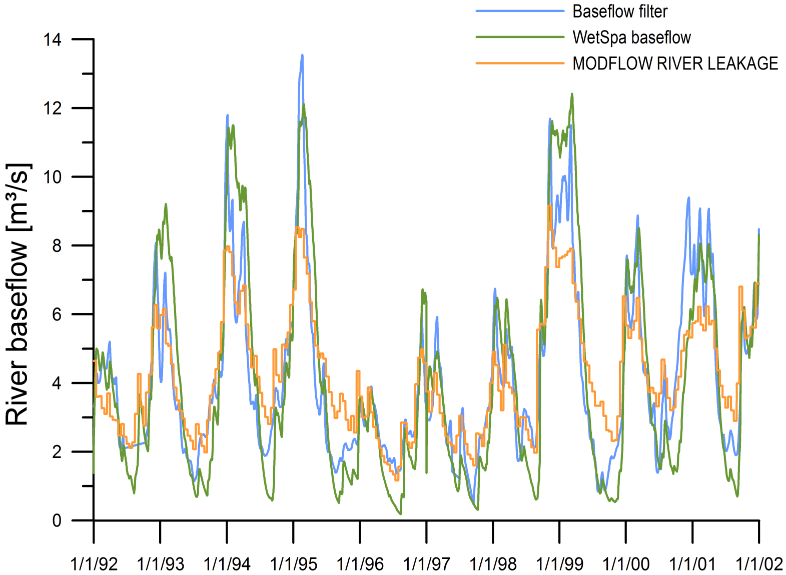

Fig. 5. Comparison of the filtered baseflow, the baseflow simulated by WetSpa and the baseflow simulated by MODFLOW.

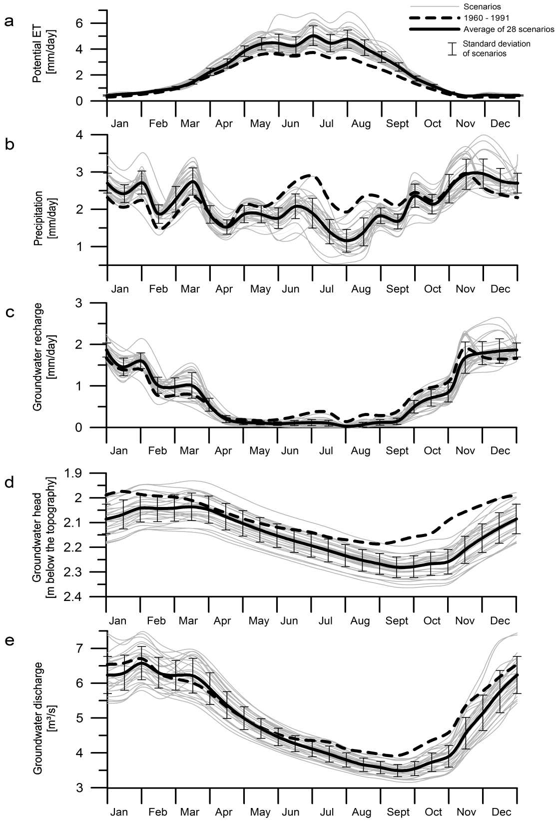

Fig. 6. Average intra-annual variability of **(a)** PET, **(b)** precipitation, **(c)** groundwater recharge, **(d)** groundwater head and **(e)** groundwater discharge for reference climate (1960–1991), 28 climate scenarios (2070–2101) and the average of the climate scenarios. One year is divided into 24 half monthly time steps, for every time step the average of 32 yr simulation is presented. Error bars represent one standard deviation between the climate scenarios.

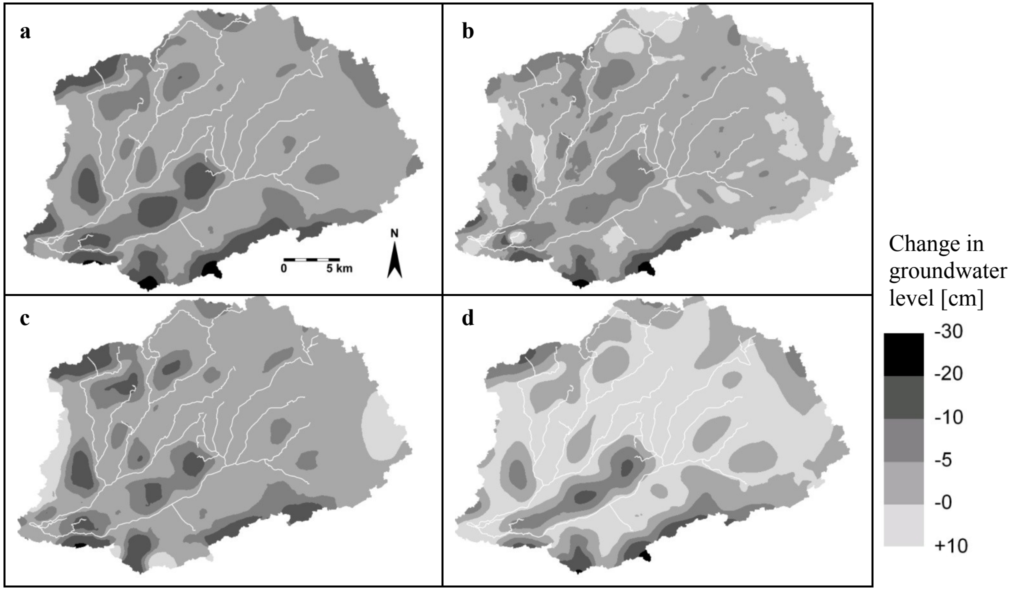

Fig. 7. Spatial distribution of the simulated change (average future minus reference) in temporally averaged: **(a)** groundwater level; **(b)** mean highest groundwater level (MHGL); **(c)** mean lowest groundwater level (MLGL); and **(d)** mean spring groundwater level (MSGL). Positive changes indicate an increase in groundwater level, negative changes indicate a decrease in groundwater level from the reference status to the average future state. Rivers are shown in white.

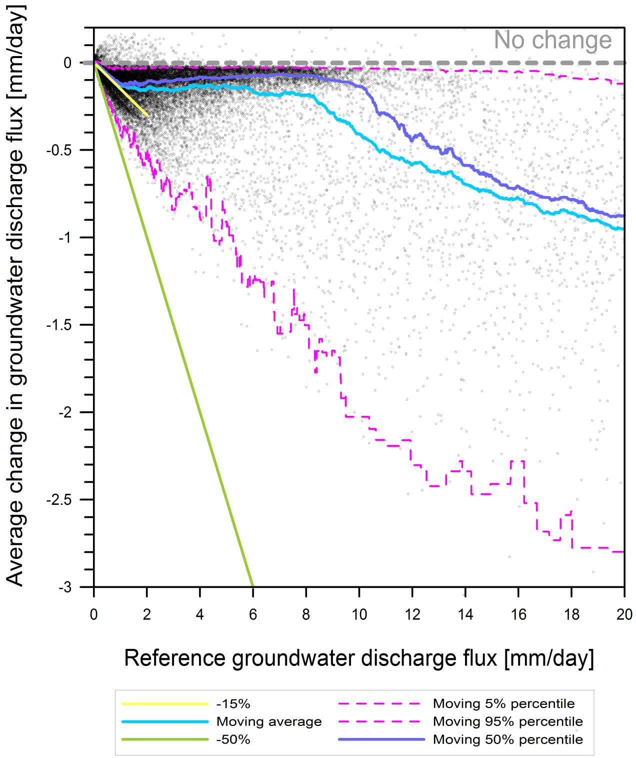

Fig. 8. Scatter-plot showing the average change, from the reference period (1960–1991) to the period 2070–2101, in groundwater discharge flux (y-axis) of all model cells related to the reference groundwater discharge flux (x-axis). The reference groundwater discharge flux is averaged over time for each model cell. The moving average and percentiles are calculated over a range of 500 values. Indicating lines show the 50 % and 15 % decrease in groundwater discharge flux.

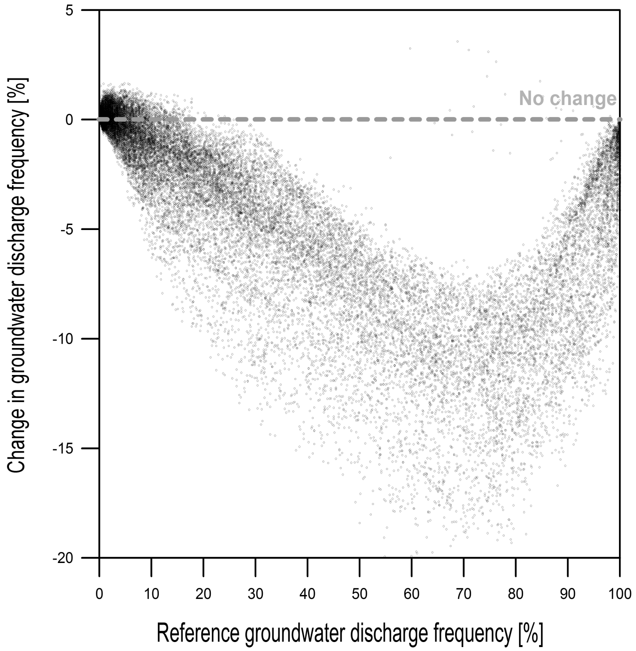

Fig. 9. Scatter–plot of reference groundwater discharge frequency (x-axis) versus the average change from the reference period (1960–1991) to the period 2070–2101 in groundwater discharge frequency (y-axis). The groundwater discharge frequency is the percentage of time that a certain model cell has a positive groundwater discharge flux, the quantity of this flux is not taken into account. Every point in the graph represents a model cell in the watershed where at least during one time step of the reference period groundwater discharge occurs.